

# A Large-Telescope Natural Guide Star AO System

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# Overview

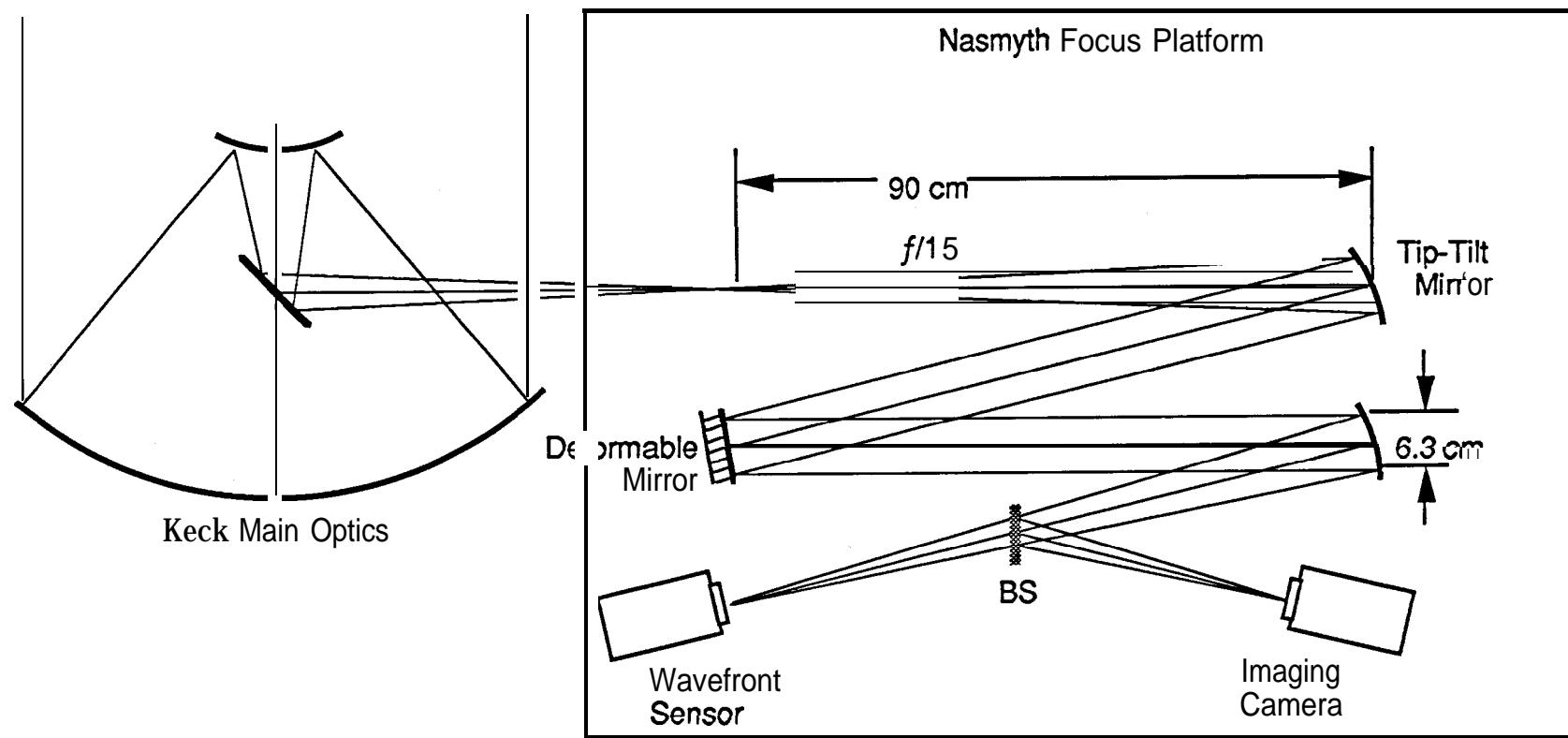
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- Keck Telescope case study
- Objectives
  - Low cost
  - Good sky coverage
- Approach
  - Natural guide star at 0.8 urn, correcting at 2.2 urn
  - Optimize system for low light levels
    - » Low-noise AO CCD detector
    - » Variable control bandwidth
    - » Spatial co-adding
- Analysis
  - Performance metric is Marechal approximation to Strehl ratio

$$SR = \exp(-\sigma^2)$$

$$\sigma^2 = \sigma_{\text{est}}^2 + \sigma_{\text{interp}}^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{delay}}^2 + \dots$$

## System Description



## System Description (cont.)

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Parameter	Symbol	Nominal Value	Good Seeing	Bad Seeing
Beacon $\lambda$	$\lambda_b$	0.8 urn	0.8 urn	0.8 urn
Science $\lambda$	$\lambda_c$	2.2 urn	2.2 urn	2.2 urn
Coherence length for science $\lambda$	$r_{0c}$	1 m	1.5 m	0.5 m
Coherence time	$\tau_{0c}$	20 ms	40 ms	10 ms

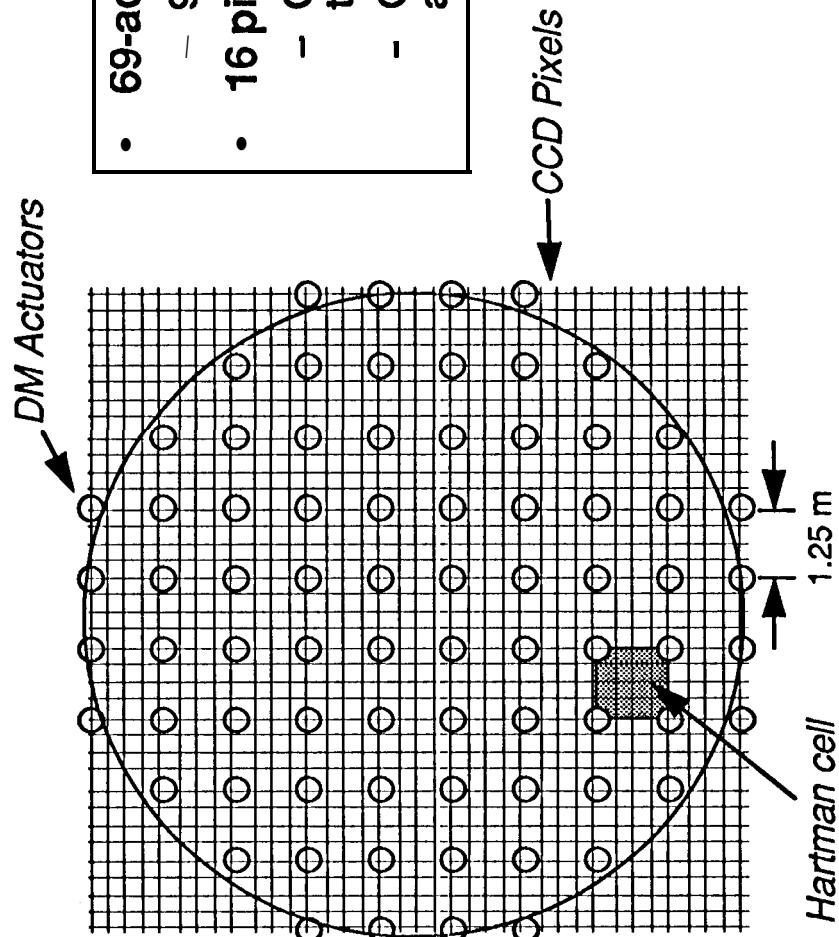
Parameter	Symbol	Nominal Value	Better AO	Worse AO
Sensor Cell Diam	$d_b$	1.25 m	1 m	1.25 m
Actuator Subap	$d_c$	1.25 m	1 m	1.25 m
WFS Quantum Efficiency	$\eta$	50%	25%	80%
WFS Band pass	$\gamma$	50%	50%	50%

## Wavefront Sensor Selection

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- Hartman vs. curvature sensor trade discussed in companion paper
- For low actuator density zonal system at assumed site conditions...
  - RMS wavefront reconstruction error from Hartman sensor was about 2x better than from curvature sensor
  - Radial derivatives of wavefront difficult to extract from curvature sensor intensity signals
- Curvature sensor maybe more competitive for...
  - Modal systems
  - Systems that require many small subapertures

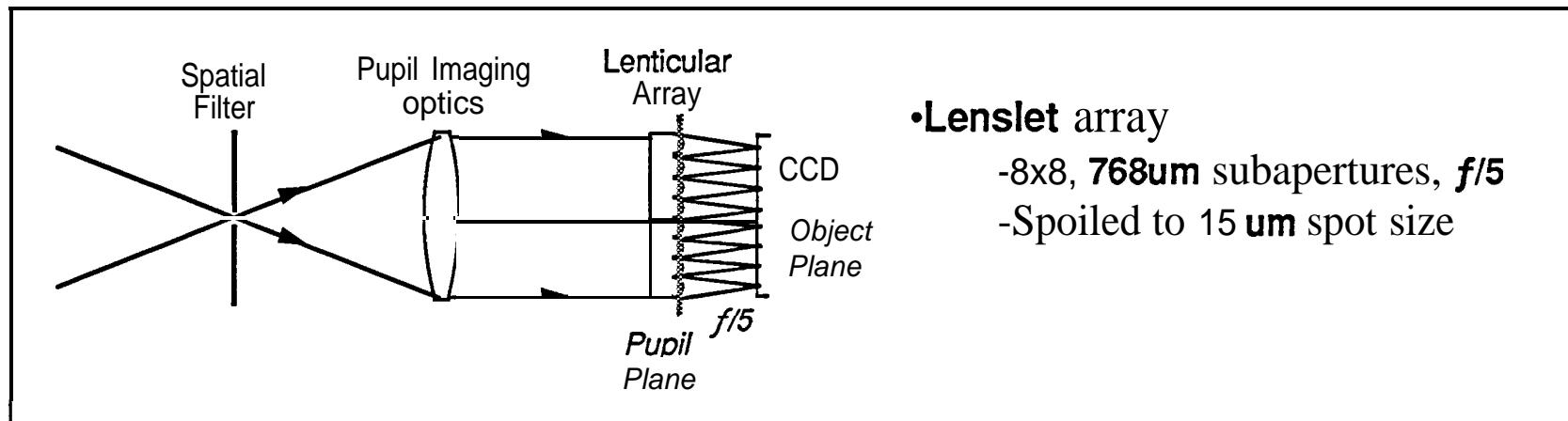
## Pupil Geometry



- 69-actuator deformable mirror
  - 9x9 grid actuates tip & tilt Hartman cells
- 16 pixels/Hartman cell (32x32 array)
  - Central 4x4 used as quad cell for tracking
  - Outer 16 increases dynamic range for acquisition

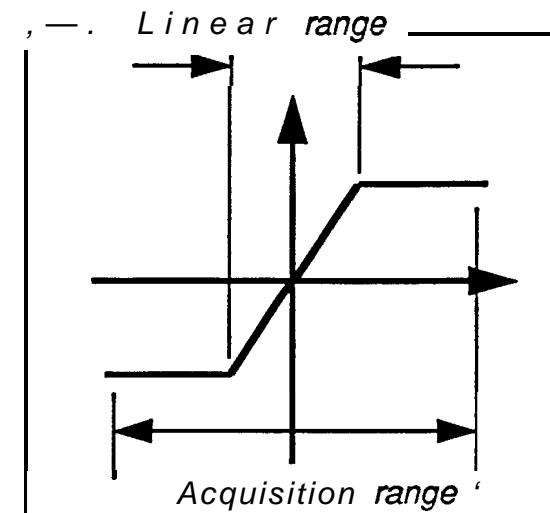
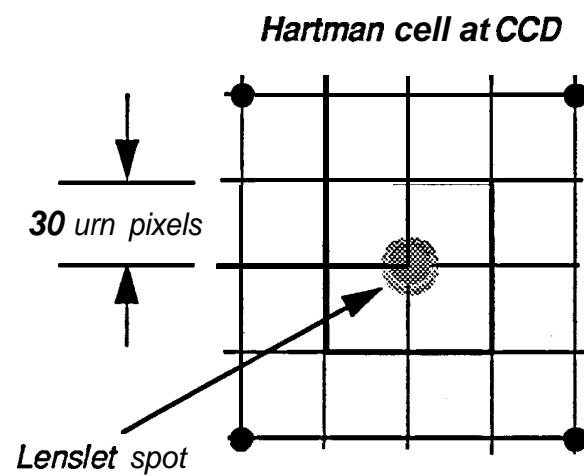
$$\sigma_{fit}^2 = \frac{1}{2} \left( \frac{d_c}{r_{0c}} \right)^{5/3}$$

# Wavefront Sensor Configuration



- **Lenslet array**

- 8x8, 768 $\mu\text{m}$  subapertures,  $f/5$
- Spoiled to 15  $\mu\text{m}$  spot size



## Detection Error

### .JPL AO-optimized 32 by 32 CCD

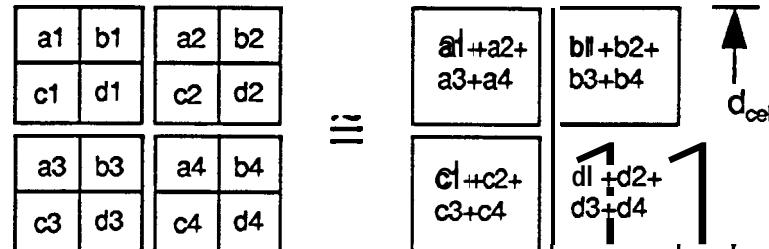
- Skipper readout amplifiers cycle at 1.5 kHz
- Read noise is averaged over many cycles

$$J_{\text{det}} = \left( \frac{1}{N} + \left( \frac{n}{N} \right)^2 \right)$$

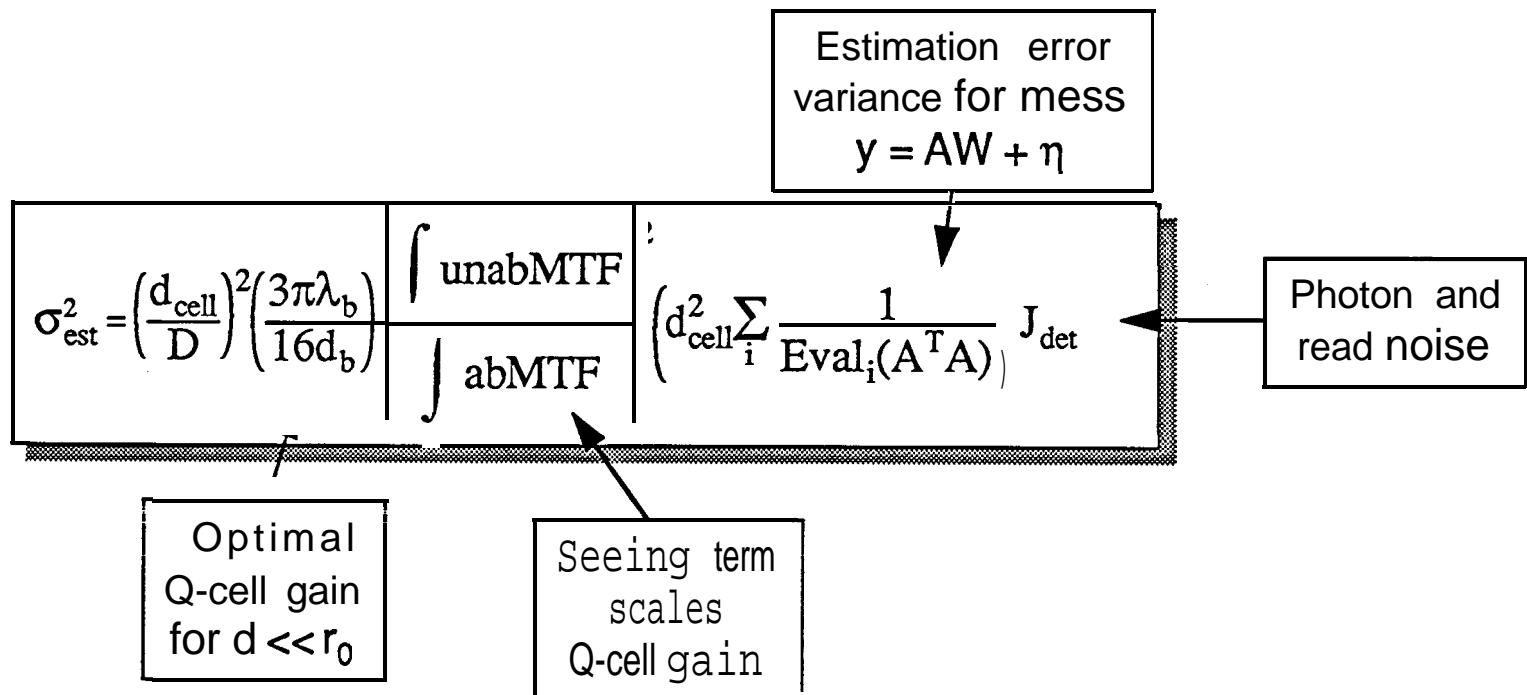
$$N = (\# \text{pix}/\text{cell}) \cdot \text{QE} \cdot \text{band} \cdot d_{\text{pix}}^2 \cdot F. \cdot 10^{-0.4 \text{ mag}} \cdot \tau_d$$

$$n = \frac{n_{\text{read}} \sqrt{(\# \text{pix}/\text{cell})}}{\sqrt{\tau_d f_{\text{skip}}}}$$

.Coadding adjacent quad cells improves S/Nat expense  
of increased fitting and estimation error



# Wavefront Estimation



$$\sigma_{\text{interp}}^2 = 0.1 \left( \frac{d_{\text{cell}}}{r_{0c}} \right)^{5/3}$$

$$\sigma_{\text{delay}}^2 = 0.96 \left( \frac{\tau_d}{\tau_0} \right)^{5/3}$$

## Summary of Analysis

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- Wavefront variance takes form:

$$\sigma^2 = C_{\text{fit}} + C_{\text{interp}} + C_{\text{esst}} \left( \frac{1}{C_N \tau_d} + \frac{C_n}{C_N \tau_d^3} \right) + C_{\text{temp}} \tau_d^{5/3}$$

- Integration time can be chosen to minimize wavefront error

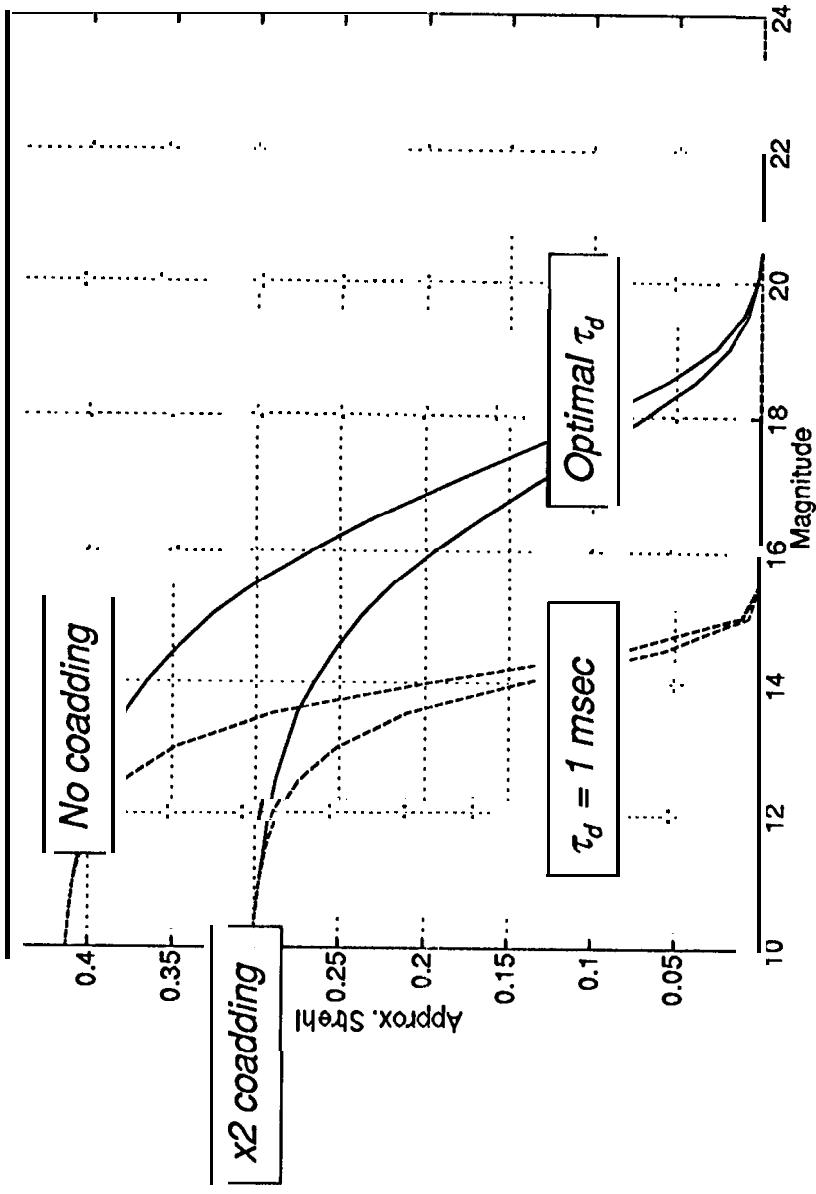
- $\tau_d$  is a zero of:

$$d(\sigma^2) = 0 \quad \Rightarrow$$

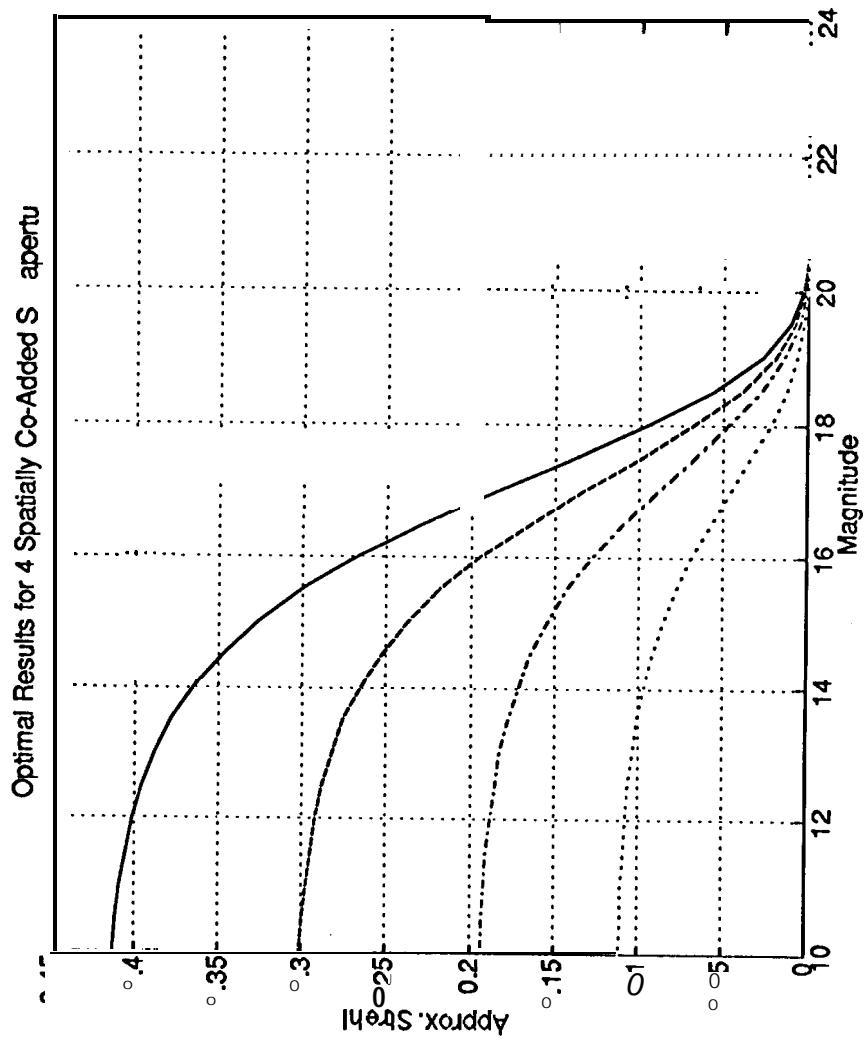
$$0 = \frac{5}{3} C_{\text{delay}} \tau_d^{14/3} - \frac{C_{\text{est}}}{C_N} \tau_d^2 - C_{\text{est}} \frac{C_n^2}{C_N^2}$$

# Optimal Integration Time

Results Comparing Optimal and Fixed  $\tau_{\text{aud}}$

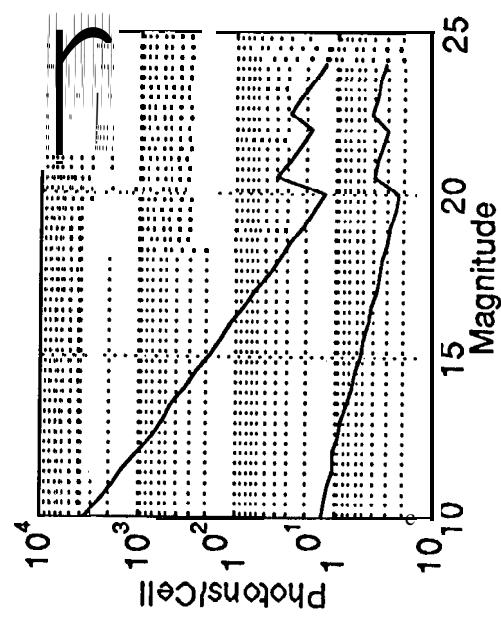
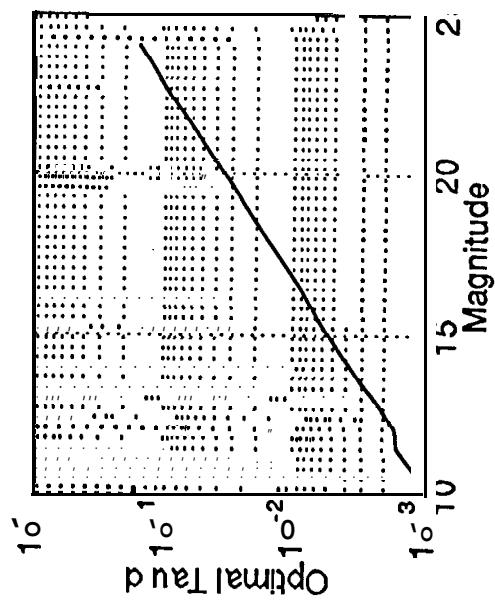
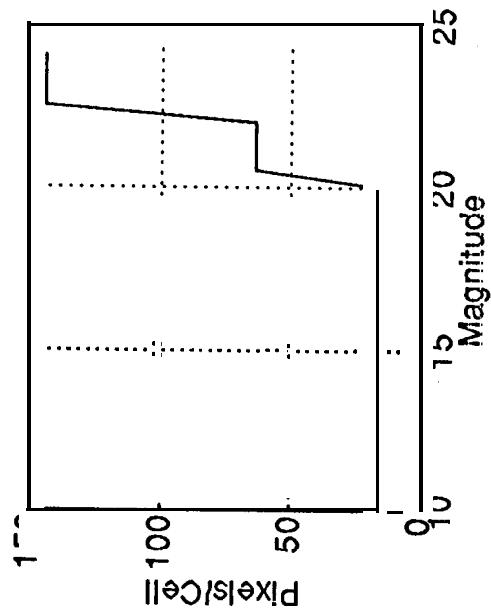
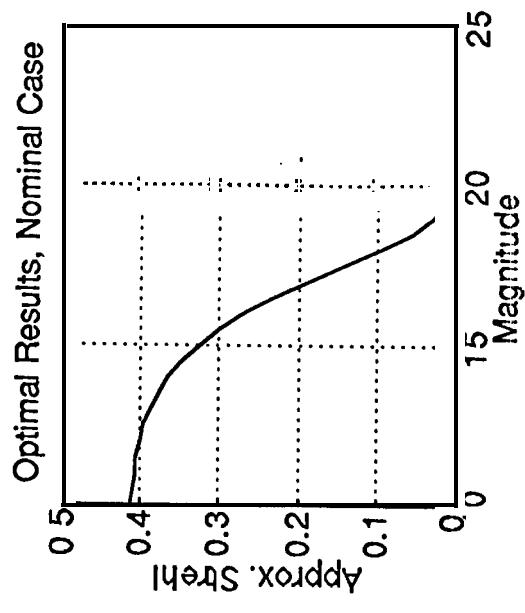


## Results for Nominal Case



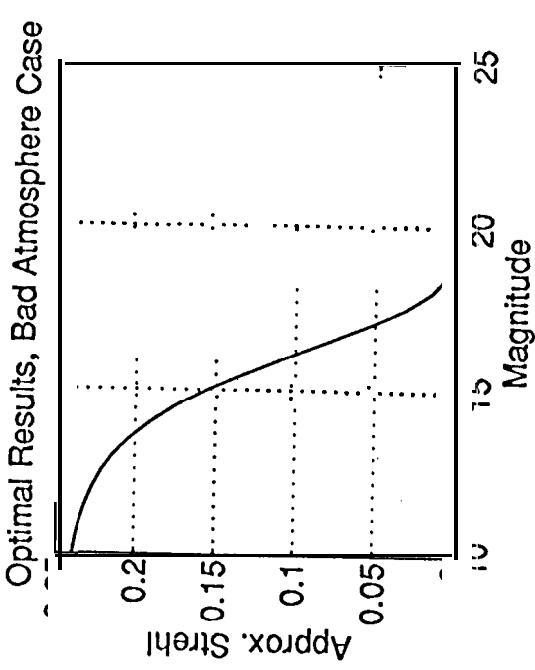
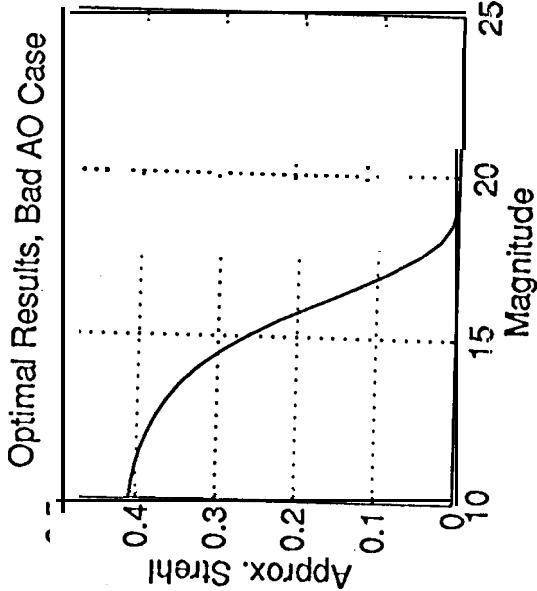
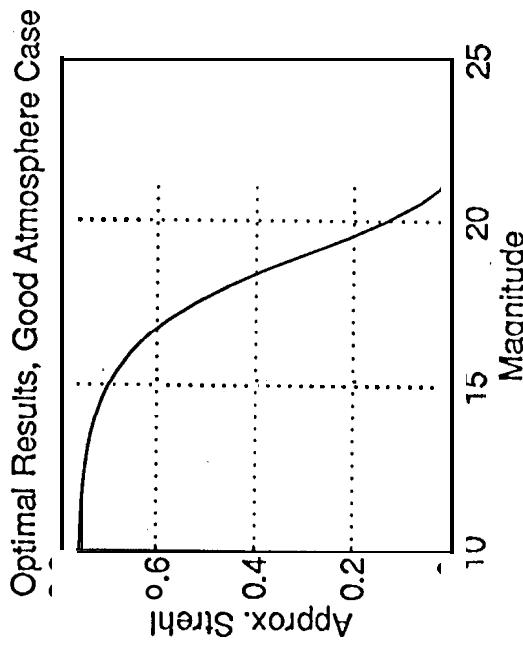
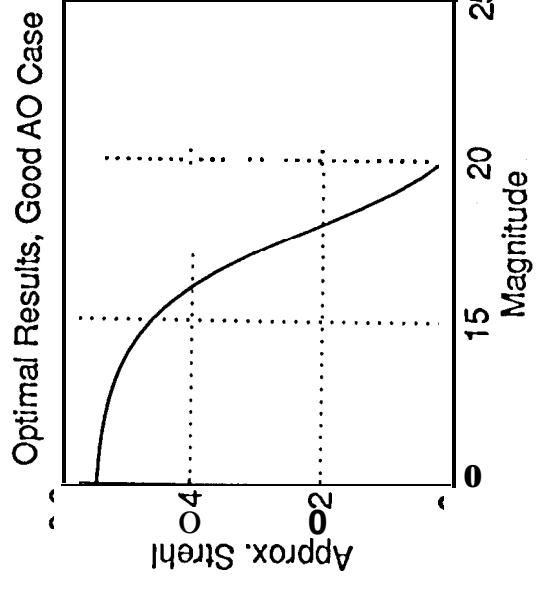
## Results for Nominal Case (cont.)

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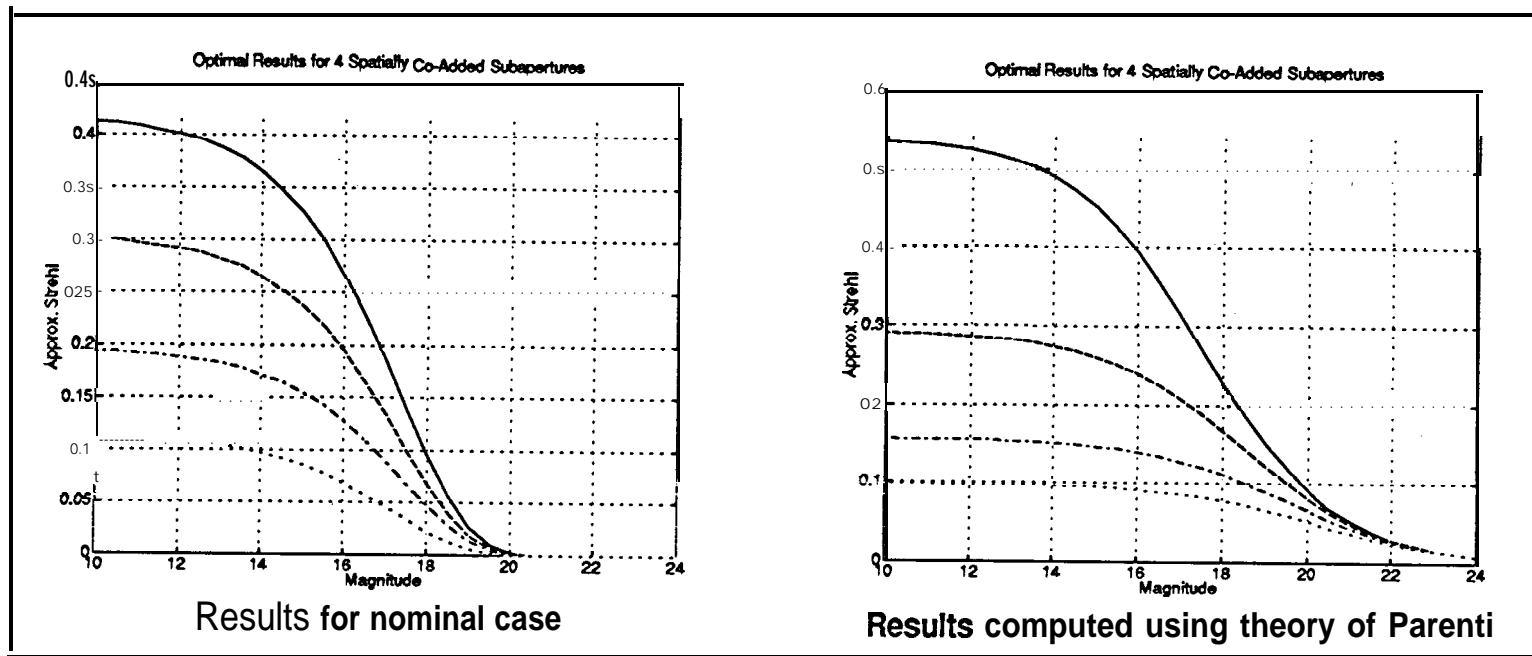


## Results for Other Cases

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# Comparison



- Differences in approach

- Estimation error neglected by Parenti - becomes important with few subapertures

- CCD vs. bicell detectors

- Noise filtering

## **Conclusions**

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- Good performance is possible for Keck with natural guide star AO system ( $SR > 0.2$  to mag 17+)
- AO-optimized CCD should be very effective
- Optimizing  $\tau_d$  is very effective
- Spatial coadding is not effective except perhaps at extreme low light levels